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Transmitted herewith for filing under 35 U.S.C. 111 and 37 C.F.R. 1.53 is the patent application of:

Leonard J. Srnka

For: **Remote Reservoir Resistivity Mapping**

Enclosed are:

- ☒ Certificate of Mailing with Express Mail Mailing Label No. **EK774501799US**
- ☒ **Nine (9)** sheets of drawings.
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Dated: September **6**, 2000

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U. S. UTILITY PATENT APPLICATION

Title: "Remote Reservoir Resistivity Mapping"

Inventors: Leonard J. Srnka

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Date: September 6, 2000

Remote mapping and analysis from the surface of the earth of hydrocarbons reservoirs at depth remains a difficult technical task. This is so despite recent advances in 3D seismic imaging, seismic direct hydrocarbon indicator (DHI) and amplitude variation with offset (AVO) analyses, and seismic attribute mapping and interpretation. Seismic detection difficulties arise in part from the fact that the mechanical properties of reservoirs, to which the seismic probe responds, are often only slightly modified when hydrocarbons replace formation waters, especially in the case of oil. The modification may be of the order of only 10's of percent. Subtle mechanical effects related to seismic wave propagation and reflection can mask DHI and AVO signatures or even produce misleading signatures. For example, low gas saturation in water sands can produce false seismic DHIs. Because of such effects, drill-well success rates are too low and exploration costs are too high in many basins. In addition, rapid and low-cost assessment of discovered undeveloped hydrocarbon reserves requires good knowledge of reservoir properties at large distances from the discovery well. Acquiring this knowledge is problematic using only seismic data. There is an urgent need to

remotely measure and map other reservoir formation properties that are sensitive to hydrocarbons, and to combine interpretation of these other properties with interpretations of seismic data and their mapped attributes. One particularly important formation property is electrical resistivity, which is strongly related to the pore fluid type and saturation.

The bulk electrical resistivity of reservoirs is often increased substantially when hydrocarbons are present. The increase can be of the order of 100's to 1000's of percent. However, increased formation resistivity alone may not uniquely indicate hydrocarbons. For instance, carbonates, volcanics, and coals can also be highly resistive. Nevertheless, spatial correlation of high formation resistivity with potential traps imaged by seismic data, or with seismic DHI or AVO effects at reservoir depth, provides strong evidence of the presence of oil or gas and valuable information on their concentrations. For example, a low gas saturation high-porosity sandstone reservoir encased in shale can produce a strong seismic DHI and an AVO curve indicative of gas. However, it would also have low electrical resistivity and hence would be a high-risk drill-well prospect.

Most hydrocarbon reservoirs are inter-bedded with shale stringers or other non-permeable intervals and hence are electrically anisotropic at the macroscopic scale. Thus, it is important to measure both the vertical (transverse) and horizontal (longitudinal) electrical resistivities of the reservoir interval. Remote measurement of the vertical and horizontal resistivities of the reservoir interval, combined with estimation of the resistivity of the non-permeable bedding, would provide quantitative bounds on the reservoir's fluid content, such as the hydrocarbon pore volume. However, there is no existing technology for remotely measuring reservoir formation resistivity from the land surface or the seafloor at the vertical resolution required in hydrocarbon exploration and production. Based on the thicknesses of known reservoirs and predicted future needs, this required resolution would be equal to or less than two percent of depth from the earth's surface or seafloor. For example, this would resolve a 200-ft net reservoir thickness (vertical sum of

hydrocarbon bearing rock thicknesses within the reservoir interval) or less at a typical 10,000-ft reservoir depth.

Overviews of electromagnetic imaging technology are given by M. N. Nabighian (ed.), *Electromagnetic Methods in Applied Geophysics*, Vols. 1 & 2, SEG Investigations in Geophysics No. 3, 1988; A. G. Nekt and B. R. Spies, *Proceedings IEEE*, v. 77, 338-362, 1989; and by M. S. Zhdanov and G. V. Keller, *The Geoelectrical Methods in Geophysical Exploration*, Elsevier, 1994. Imaging of electrically conductive objects such as ore bodies has been the dominant application for electromagnetic methods. In applications for hydrocarbon exploration, most of the technology was developed to image large geological structures in regions where seismic data are low in quality or are absent, and little other geological or geophysical information is available.

Direct exploration for hydrocarbons using surface-based electromagnetic imaging has been attempted since the 1930s, but with little commercial success. This lack of success is due to the low spatial resolution and the ambiguous interpretation results of current electromagnetic methods, when applied in stand-alone and spatially under-sampled ways to the geological imaging problem. Low subsurface resolution is one consequence of the diffusive nature of the low frequency electromagnetic waves, that is, below 1 kHz, required to penetrate the earth to reservoir depths. The vertical resolution of such electromagnetic waves is relatively insensitive to bandwidth, unlike the seismic case, but is very sensitive to the accuracy and precision of phase and amplitude measurements and to the inclusion of constraints from other data. That is, the unconstrained geophysical electromagnetic data inverse problem is mathematically ill posed, with many possible geologic structures fitting electromagnetic data equally well. Consequently, the vertical resolution of unconstrained electromagnetic imaging is typically no better than 10 percent of depth. This gives a resolution of only a 1000-ft net reservoir thickness at a typical 10,000-ft reservoir depth. However, within a given resolved layer, conventional resistivity measurement accuracy can be within a factor of two, which is adequate for oil and gas exploration.

Electromagnetic technology that is applicable to direct reservoir imaging uses electrically grounded controlled sources to produce vertical and horizontal current flow in the subsurface at the reservoir depth. The five embodiments of this technology, well known within the electromagnetic imaging community, are: (1) the LOTEM method described by K. M. Strack, *Exploration with Deep Transient Electromagnetics*, Elsevier, 1992; (2) the SIROTEM method, described by Buselli in US patent 4,247,821; (3) CGG's TRANSIEL[®] system, described in US patent 4,535,5293; (4) the EMI method, described by Tasci et al. in US patent 5,563,513; and (5) the WEGA-D method described by B. W. Smith and J. Dzwinel in *WEGA-D SYSTEM*[®], WEGA-D Geophysical Research Ltd., 1984. A newer version of WEGA-D named PowerProbe[®] has been developed by the Canadian company Enertec, a successor to WEGA-D Geophysical Research. All five methods suffer from the vertical resolution limitation of approximately 10% of depth cited above, which makes them unsuitable for direct reservoir imaging except for unusually thick reservoirs. This resolution limitation results from one or more of the following deficiencies in each method: (1) lack of means to focus the electromagnetic input energy at the target reservoir; (2) spatial under-sampling of the surface electromagnetic response fields; (3) measurement of only a few components (usually one) of the multi-component electromagnetic surface fields that comprise full tensor electromagnetic responses at each receiver (except for WEGA-D/PowerProbe); (4) data processing using 1-D, 2-D, or pattern recognition algorithms rather than full 3-D imaging methods; and (5) lack or paucity of explicit depth information and resistivity parameter values incorporated into the data processing to constrain the inversion results.

Another serious limitation in these five methods is their use of high-impedance contact electrodes and connecting wires, with greater than 1 Ohm total series resistance, to transmit the source current into the subsurface. This output impedance is primarily a result of the small surface area of the electrodes that contact (i.e. ground to) the earth. High output impedance severely limits the electrical current at the reservoir depth, which in turn reduces the strengths of the surface electromagnetic responses to the

subsurface reservoir for a given source power. Current limitation due to high-impedance sources also results in reduced depths of exploration, especially in electrically conductive sedimentary basins. The effective depth of electromagnetic exploration increases as a fractional power of source strength, between $M^{1/5}$ and $M^{1/3}$ for grounded electric dipole sources where M is the dipole moment, that is, current multiplied by dipole length. The exponent depends upon which surface field component is measured, but in general short-offset (or "near-field") electromagnetic receiver responses have the best sensitivity to deep targets, as shown in B. R. Spies, *Geophysics* v. **54**, 872-888, 1989.

V. S. Mogilatov and B. Balashov, *J. Appl. Geophys.*, v. 36, 31-41, 1996; and Mogilatov's Russian patent 2,084,929-C1 describe the use of surface electric concentric ring dipoles and radial electric bipoles. A. G. Tarkov, *Bull. Acad. Sci. U.S.S.R., Geophys. Ser.*, no. 8, 11, 1957, R. N. Gupta and P. K. Bhattacharya, *Geophysics*, v. 28, 608-616, 1963, and by A. Dey et al., *Geophysics*, v. 40, 630-640, 1975 describe the use of opposite-polarity collinear surface electric bipoles ("unipoles"). However, ring electrodes described by Mogilatov and Balashov do not contain discussions of, much less calculations for, the optimum electrode dimensions needed to maximize the vertical electric field or current density at the target (reservoir) depth. The unipole methods described by Tarkov, Gupta, Bhattacharya, and Dey et al. do not include discussions of or calculations for the effects of changing the source frequency, or the effects of using finite-length unipoles (second electrodes not at infinite distance), on the optimum configuration needed to maximize the vertical electric field or current density at the target depth.

S. K. Verma and S. P. Sharma, *Geophysics*, v. 60, 381-389, 1995 and H. Maurer and D. E. Boerner, *Geophys. J. Int.*, v. **132**, 458-468, 1998 discuss optimization of surface electromagnetic source array configurations in order to best focus energy onto subsurface targets. However, Verma and Sharma restrict their discussion to subsurface conducting layers, and do not include unipole or concentric ring dipole arrays in their calculations. Maurer and Boerner discuss the more general problem of optimization of surface

electromagnetic surveys for imaging subsurface targets, but do not discuss unipole, multiple radial bipole, or concentric ring dipole sources.

Conventional geophysical electromagnetic data processing finds the minimum earth structure, that is, the simplest resistivity model, which is consistent with the measured data within the experimental error bounds, but without explicit incorporation of *a priori* information. Incorporation of hard constraints into the data processing significantly improves spatial resolution and resistivity accuracy, which are not simply related to signal wavelength or bandwidth as in the seismic case. Examination of well log and other data shows that, in most cases, major seismic boundaries are also major resistivity boundaries. In addition, interpretation of seismic, gravity, and magnetic data would provide good knowledge of the major lithologies present in a prospective area before drilling. Applying constraints for a large number, (10's to 100's) of layers and other major geologic boundaries (for instance, faults) would be novel for electromagnetic imaging of hydrocarbon reservoirs.

Two previous methods have described the incorporation of seismic constraints to improve spatial resolution in low-frequency electromagnetic geophysical inversion. Although not applied to hydrocarbon reservoir imaging, a method was developed by G. M. Hoversten et. al., *Geophysics*, v. 63, 826-840, 1998a; and *SEG Annual Meeting Expanded Abstracts*, v. 1, 425-428, 1998b to improve 2-D natural-source electromagnetic (magnetotelluric) imaging of the base of salt structures in the offshore Gulf of Mexico. Vertical resolution of the salt base improves by a factor of 2 to 3 when the depth to the top of salt is constrained by 3-D seismic data and when the salt resistivity is fixed. Natural-source methods such as that of Hoversten et al. lack the vertical resolution required for direct imaging of resistive hydrocarbon reservoirs, because they measure the earth's response to the flow of horizontal subsurface electrical currents that are insensitive to regions of increased resistivity. D. L. Alumbaugh and G. A. Newman, *Geophys. J. Int.*, v. 128, 355-363, 1997; and *SEG Annual Meeting Expanded Abstracts*, v. 1, 448-451, 1998 have described the use of seismic constraints to improve resolution in cross-well electromagnetic imaging within hydrocarbon

reservoirs, in a manner similar to that of Hoversten et al. for surface magnetotelluric data. However, the cross-well method requires the existence of at least two wells that penetrate the reservoir.

Estimation of the reservoir's fluid type, saturation, and shaliness factor from surface geophysical measurements has been previously conducted using only seismic reflection data, in particular various seismic interval attributes (amplitude widths, ratios, phases, etc.). Here, the shaliness factor is the ratio of net hydrocarbon bearing zone thickness (pay) to gross reservoir thickness. It is well known in the industry that the electromagnetic response of a vertically layered earth depends on the direction of the resistivity measurement. See, for instance, M. S. Zhdanov and G. V. Keller (1994, *op. cit.*). However, there is no existing remote (surface-based) electromagnetic method for measuring both the separate vertical and horizontal resistivities of a reservoir interval at depth. Directional resistivity measurements for reservoirs have been restricted to *in-situ* methods, such as well logging.

Specific technologies for indirect electromagnetic detection of reservoired hydrocarbons at depth have also been developed, but these rely on the detection of electrically altered zones ("chimneys") above reservoirs caused by the purported slow leakage of hydrocarbons upward from the reservoir.

20 The existence and relationships of alteration chimneys to reservoired hydrocarbons have not been unequivocally demonstrated. Changes in resistivity (increases and decreases) and polarizability (or induced polarization) are claimed by the practitioners of chimney detection to occur at various locations within such chimneys. Electromagnetic methods to locate

25 chimneys were developed by Sternberg et al., as described in their US patent 4,446,434, and Tasci et al., as described in their US patent 5,563,513. The TRANSIEL[®] and WEGA-D/PowerProbe systems can also be used to detect hydrocarbon chimneys. These methods suffer the same depth resolution limitations as listed above, for the reasons cited in the preceding paragraph.

SUMMARY OF THE INVENTION

The invention is a method for surface estimation of reservoir properties of a subsurface geologic formation. First, the location of and average earth resistivities above, below, and horizontally adjacent to the subsurface geologic formation are determined, using geological and geophysical data in the vicinity of the subsurface geologic formation. Second, the dimensions and probing frequency for an electromagnetic source are determined to substantially maximize transmitted vertical and horizontal electric currents at the subsurface geologic formation, using the location and the average earth resistivities. Next, the electromagnetic source is activated at or near surface, approximately centered above the subsurface geologic formation and a plurality of components of electromagnetic response are measured with a receiver array. Next, geometrical and electrical parameter constraints are determined, using the geological and geophysical data. Finally, the electromagnetic response is processed using the geometrical and electrical parameter constraints to produce inverted vertical and horizontal resistivity depth images.

In an alternative embodiment, the inverted resistivity depth images may be further combined with the geological and geophysical data to estimate the reservoir fluid and shaliness properties.

In a further alternative embodiment, the average earth resistivities above, below, and horizontally adjacent to the subsurface geologic formation are verified using the plurality of components of electromagnetic response measured with the receiver array.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention and its advantages may be more easily understood by reference to the following detailed description and the attached drawings in which:

FIG. 1 is a perspective view of the preferred embodiment of the layout of the source and receiver apparatus used in the present invention for remote estimation of reservoir resistivities;

FIG. 2 is a perspective view of an alternative embodiment of the layout of the source and receiver apparatus used in the present invention for remote estimation of reservoir resistivities;

FIG. 3 is a plot of the axial vertical electric field complex magnitude $|E_z|$ as a function of the ratio of inner electrode radius over depth, a/d , for various values of the ratio of the inner electrode radius over electromagnetic skin depth, a/δ ;

FIG. 4a is a plot of the axial vertical electric field complex magnitude $|E_z|$ versus the ratio of inner electrode radius over the depth, a/d ;

FIG. 4b is a plot of the axial vertical electric field complex magnitude $|E_z|$ versus the ratio of inner electrode radius over the electromagnetic skin depth, a/δ ;

FIG. 5a is a plot of the axial vertical electric field complex magnitude $|E_z|$ versus the ratio of outer electrode radius over the inner electrode radius, b/a ;

FIG. 5b is a plot of the total electrode current versus the ratio of outer electrode radius over the inner electrode radius, b/a ;

FIG. 6 is a perspective view showing the configuration of the alternative embodiment of the layout of the source and receiver apparatus used in the present invention for remote estimation of reservoir resistivities, as used in the example;

FIG. 7 illustrates a bipolar square current waveform as output by the electromagnetic power source for use in the method of the present invention;

FIG. 8 is a plot of the real part of the calculated radial component E_r of the surface electric field response from the example; and

FIG. 9 is a flowchart illustrating the processing steps of an embodiment of the method of the present invention for surface estimation of reservoir properties.

While the invention will be described in connection with its preferred embodiments, it will be understood that the invention is not limited thereto.

On the contrary, it is intended to cover all alternatives, modifications and equivalents that may be included within the spirit and scope of the invention, as defined by the appended claims.

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DETAILED DESCRIPTION OF THE INVENTION

The invention is a method whereby the average vertical and horizontal formation resistivities of a hydrocarbon reservoir are remotely mapped from the land surface or the seafloor, using low-frequency electromagnetic waves constrained by seismic depth imaging and other *a priori* information about the subsurface. The invention overcomes the electromagnetic low vertical resolution problem by a combination of data acquisition and processing steps that are targeted at mapping the resistivity of a previously located or prospective reservoir.

One embodiment of the layout of the apparatus used in the invention is shown in Figure 1. In general, the invention uses the following four features that are synergistic in their combination: (1) a high-current multi-mode optimized electromagnetic source, (2) a multi-component receiver array, (3) 3-D wave-equation data processing, and (4) reservoir properties estimation and mapping. These four features will be described in turn.

In this embodiment of the present invention, two continuously grounded electrodes 4, 5, each consisting of one or more uninsulated electrical conductors, are buried at or within the near surface of the earth or the seafloor 1 in concentric circles of radii **a** and **b** respectively. Preferably, the electrodes are buried in the top zero to three meters. Alternatively, for offshore applications, the electrodes may be suspended or towed in the seawater above the seafloor as described by L. J. Srnka in U.S. Patent No. 4,617,518. This electrode configuration provides for substantially maximizing a transmitted vertical electrical current to a reservoir target 3 at depth **d** within the earth 2. In an alternative embodiment, an optional insulated circular loop 6, consisting of one or more electrically insulated conductors, is arranged at the earth's surface or seafloor 1 in a circle of radius **c** concentric to the two

continuously grounded electrodes 4, 5, for inducing horizontal electrical currents at the reservoir 3. Although the insulated circular loop 6 is shown positioned between the two continuously grounded electrodes 4, 5 in Figure 1, the insulated circular loop 6 could be positioned inside the inner grounded electrode 4 or outside the outer grounded electrode 5. This insulated loop source 6 is used to augment natural background electric and magnetic field variations in the earth, to provide additional induced horizontal currents at the reservoir depth. The two grounded electrodes 4, 5 and the optional insulated source loop 6 are connected to one or more variable-frequency (preferably, 10^{-4} - 10^4 Hz) high current (preferably, 10^2 - 10^6 Amperes) electrical power sources and controllers 7 by means of connecting cables 8, 9, preferably positioned radially. In the case of multiple sets of power sources and controllers 7, the connecting cables 8, 9 are preferably positioned equally around the circumferences of the grounded electrodes 4, 5. The power sources and controllers 7 may be located at the land surface or seafloor 1. Alternatively, in the case of offshore surveys, the power sources and controllers 7 may be located at the sea surface, or within the body of the sea. The power sources and controllers 7 provide for selective excitation of the grounded electrodes 4, 5 and insulated wire loop 6, modifying the frequency as required to maximize the subsurface response.

The dimensions and probing frequency for a given reservoir depth and average earth resistivity, plus the corresponding electrical impedance of the grounded electrodes 4, 5, are calculated by numerically solving the uninsulated buried low-frequency electromagnetic antenna problem. Preferably, this problem is solved using the methods of R. W. P. King and G. S. Smith, *Antennas in Matter*, MIT Press, Cambridge, 1981. Preferably, the solution is implemented by means of a 3-D frequency-domain computer program in which the surface potentials, current densities, and electric fields are found by solving Maxwell's equations using 2-D complex Fourier transforms at each depth interval. Boundary conditions for solving the problem are applied to enforce the condition that, at each frequency, the total current leaving the inner ring 4 equals the total current captured by the outer

ring 5, and that the voltage difference between the rings 4, 5 is conserved. Preferably, the values of radii **a** and **b** are determined by substantially maximizing the vertical and horizontal electric fields at the symmetry axis of the concentric rings 4, 5 (radius $r = 0$) at the depth of the center of the reservoir. FIGS. 3, 4a, 4b, 5a, and 5b show results from this calculation for sample input values. The sample input values affect the absolute values of the electric fields and currents, but do not affect the dimensionless scaling parameters used to optimize the source electrodes. Thus, in FIGS. 3, 4a and 4b, the shape of the curves would remain the same for the same ratio of outer electrode radius to inner electrode radius $b/a = 8$, while the absolute magnitude of the curves would change for different values of average earth resistivity and source excitation voltage. Similarly, in FIGS. 5a and 5b, the shape of the curves would remain the same for the same ratio of depth to inner electrode ratio $d/a = 2/3$, while the absolute magnitude of the curves would change for different values of average earth resistivity and source excitation voltage. These ratios and values were selected for illustrative purposes only and should not be taken as limitations of the method of the present invention.

FIG. 3 gives the axial (radius $r = 0$) vertical electric field complex magnitude $|E_z|$ (in millivolts/meter) as a function of a/d for various values of the ratio a/δ , per unit voltage (1 Volt) of source excitation between the grounded electrode rings 4, 5, where $\delta = 503 \times (\rho/f)^{1/2}$ is the electromagnetic skin depth in meters. Here, ρ is average earth resistivity and f is source excitation frequency.

FIGS. 4a and 4b are plots of the axial vertical electric field complex magnitude $|E_z|$ versus the ratio of inner electrode radius over the depth, a/d and the ratio of inner electrode radius over the electromagnetic skin depth, a/δ , respectively. FIGS. 3 and 4a show that the axial $|E_z|$ is maximized when $a/d \approx 3/2$ and $a/\delta \approx 2/3$. Thus, $|E_z|$ is maximized when $d/\delta = (a/\delta)/(a/d) \approx 9/4$, as shown in FIG. 4b.

FIGS. 5a and 5b show the dependence of axial $|E_z|$ and total electrode current on the ratio of outer electrode radius over the inner electrode radius, b/a , per unit source voltage. A value of $b/a \geq 9$ maximizes $|E_z|$ at the reservoir.

- 5 Preferably, the radius c of the insulated ring source 6 (vertical magnetic dipole) is $c \leq a$, based on results from B. R. Spies (1989, *op. cit.*) for electromagnetic inductive sounding in the near-field zone of a vertical magnetic dipole source.

- 10 An alternative embodiment of the grounded electrodes is shown in FIG. 2. The two concentric ring electrodes 4, 5 of respective radii a and b are replaced by six or more linear grounded electrodes 11 of equal lengths $L = b - a$. Preferably, these electrodes 11 will be continuously grounded to the earth along their entire individual lengths L . Alternatively, the electrodes 11 may be only partially grounded, that is, continuously grounded only within some distance $\gamma \leq L/2$ as measured from the radii a and b , respectively, as shown in FIG. 6. Preferably, the electrodes 11 are placed along radii separated by equal angles of not more than 60° , whose inward radial projections intersect at the center of the electrode array. Preferably, each linear electrode 11 is connected at each of its ends ($r = a$ and $r = b$) to a continuously grounded linear terminating electrode 12 that is substantially orthogonal (preferably, $90^\circ \pm 10^\circ$) to the connected radial electrode 11. Preferably, the length of each terminating electrode 12 is not more than $L/10$. Preferably, one or more power sources and controllers 7 are connected to the radial linear electrodes 11 near the midpoints $L/2$ of the electrodes 11 within a distance of $\pm L/10$. If more than one power source 7 is used simultaneously, the multiple sources 7 operate in a synchronized manner to supply electrical current to each electrode 11. Preferably, source synchronization is such that the total phase variations of the six or more source currents do not exceed 0.1 degree and the total amplitude variations of the source currents do not exceed 0.1 percent. In this alternative embodiment employing grounded electrodes 11, the optional insulated circular wire loop 6 may also be used, as described

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The spatial positions and orientations at the earth's surface or seafloor 1, of the source electrodes 11, and of the receivers 10 in the array are measured. Preferably, the positioning and orientation is accomplished using geodetic methods standard in the industry and well known to those of skill in the art. These geodetic methods may include differential and kinematic GPS (Global Positioning Satellite), and acoustic transponders in an offshore application. Preferably, maximum allowed position uncertainties are ± 0.001 d in the vertical and the two horizontal directions. Preferably, maximum allowed orientation uncertainties are ± 0.10 degrees in the vertical and in the two horizontal orientations.

Preferably, standard electromagnetic industry data processing techniques such as those described by M. N. Nabighian (1988, *op. cit.*); K.-M. Strack

(1992, *op. cit.*); G. Buselli and M. Cameron, *Geophysics*, v. **61**, 1633-1646, 1996; and G. D. Egbert *Geophys. J. Int.*, v. **130**, 475-496, 1997 are used for suppression of both natural background and human-generated electromagnetic noise. Preferably, data redundancy from multiple-receiver

5 multi-component responses and from many source repetitions, combined with local noise measurements and signal cross-correlation techniques, are used within these standard methods to achieve noise suppression. Preferably, such techniques are applied to the data to produce a signal-to-noise ratio greater than or equal to 1 and signal accuracy greater than or equal to 1.0%

10 for each electromagnetic component used within the multi-component data inversion.

The electromagnetic source signature (source-generated noise) is suppressed automatically by the self-canceling field geometry of the grounded electrodes (4 and 5 in FIG. 1, 11 and 12 in FIG. 2), as described by Mogilatov

15 and Balashov (1996, *op. cit.*). Additional suppression (deconvolution) of source effects is accomplished by normalizing the receiver data to the background earth response using standard industry techniques well known to one of skill in the art, such as described in M. Zhdanov and G. Keller, (1994, *op. cit.*) or K. M. Strack (1992, *op. cit.*). Alternatively, this suppression may be

20 accomplished by normalizing (cross-referencing) the data using apparent resistivity functions for a layered earth as described in T. G. Caldwell and H. M. Bibby, *Geophys. J. Int.*, v. **135**, 817-834, 1998.

Preferably, the data from the array of receivers 10 are converted ("inverted") from time or frequency domain electromagnetic responses into a

25 3-D resistivity depth image of the earth by the application of iterative 3-D model-guided nonlinear electromagnetic inversion methods that incorporate geometrical and electrical parameter constraints, as will be described below. Finite-difference and finite-element 3D models may be used. Inversion methods used in this invention include standard techniques such as quasi-

30 linear regularized methods, such as described in M. S. Zhdanov and S. Fang, *Radio Sci.*, v. **31**, 741-754, 1993 and fully nonlinear conjugate gradient or Gauss-Newton methods, such as described in G. A. Newman and D. L.

Alumbaugh, Report SAND96-0582, Sandia National Laboratories, 1996; and
Geophys. J. Int., v. **128**, 345-354, 1997; Alumbaugh and Newman *op. cit.*,
 1997 and *SEG Annual Meeting Expanded Abstracts*, v. 1, 456-459, 1998.

Preferably, the positions and strengths of all source currents applied at or
 5 within the surface of the land surface and at, above, or within the seafloor 1
 are explicitly included in the inversion, by means of Green's functions or other
 standard mathematical techniques that are well known to one of skill in the
 art. Preferably, separate inversions are performed for receiver data collected
 using the grounded electrode sources (4 and 5 in FIG. 1, 11 and 12 in FIG. 2)
 10 and for receiver data collected using the insulated loop source 6 and the
 earth's natural background magnetotelluric source when the other sources are
 turned off. Preferably, joint inversions of receiver data collected using any
 combination of the grounded source (4 and 5 in FIG. 1, 11 and 12 in FIG. 2),
 insulated source 6, and magnetotelluric source are also performed.

15 Preferably, the spatial positions of geometrical constraints are obtained
 from surfaces, such as horizons and faults, interpreted in dense 2-D or in 3-D
 depth-converted stacked seismic reflection data. Preferably, standard
 industry seismic interpretation packages, such as Geoquest IESX[®], Paradigm
 GeoDepth[®], or Jason Workbench[®], are used to produce the interpreted
 20 seismic surfaces, to tie the seismic depth data to well log, gravity, magnetic,
 and other geoscience data, and to transfer these depth surfaces to the 3-D
 electromagnetic inversion starting model. Resistivity values for the initial
 electromagnetic depth model for geologic units bounded by the interpreted
 seismic surfaces are produced by any of a number of standard industry
 25 methods well known to one skilled in the art. These methods include ties to
 log data; extrapolation from regional data bases; application of empirical
 resistivity transforms using seismic intervals, well sonic velocities, or acoustic
 impedances; and initial layered-earth (1-D) resistivity inversion derived from
 the collected electromagnetic receiver data. Preferably, constraints are
 30 enforced during the inversion using standard industry techniques, such as
 described in M. A. Meju, *Geophysical Data Analysis: Understanding Inverse
 Problems and Theory*, Society of Exploration Geophysicists, 1994. These

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standard techniques include Tikhonov regularization, Bayesian methods, sharp-boundary approaches (G. Hoversten et al., 1998, *op. cit.*), equivalent integral conductance and resistance methods, and minimum gradient support techniques (O. Portniaguine and M. Zhdanov, 1998, *op. cit.*).

- 5 In an alternative embodiment of the invention, interpretation of the inverted resistivity depth cubes ("inversions") includes comparison of the 3-D resistivity-depth values with interpreted 3-D seismic features and all mapped attributes derived from the seismic data (pre-stack and post-stack). Preferably, the separate and mathematically joint electromagnetic inversions
10 produced from the grounded electrode sources and from the insulated loop source and magnetotelluric source are compared and combined with each other and with the seismic reflection features and seismic attributes to estimate the fluid type, hydrocarbon pore volume, saturation, and the shaliness factor (net pay-to-gross reservoir thickness ratio) within the
15 reservoir over its mapped extent. The reservoir may be seismically defined by a combination of stratigraphic or structural closure or limits of mapped seismic attributes.

- The preferred method of this alternative embodiment of the invention to estimate fluid type, hydrocarbon pore volume, saturation and shaliness factor
20 is as follows. The resistivity inversion at the reservoir depth produced from electromagnetic receiver data collected using the grounded electrode sources is used to measure the vertically averaged resistivity ρ_{vert} within the reservoir
3. The resistivity inversion at the reservoir depth produced from electromagnetic receiver data collected using the insulated source or the
25 magnetotelluric source is used to measure the horizontally averaged resistivity ρ_{horiz} within the reservoir. A facies model of the reservoir is derived from the seismic interpretation, geologic concepts, and available facies data (such as well logs and data bases). This facies model is combined with the
 ρ_{vert} and ρ_{horiz} inversion measurements to estimate products and ratios of the
30 permeable bed resistivity ρ_{ss} , the summed permeable bed thickness divided by the total reservoir interval thickness **ntg** ("net-to-gross"), and the impermeable bed resistivity ρ_{sh} . For a reservoir facies model comprised of

uniform values ρ_{ss} for the permeable beds, and a different but uniform value ρ_{sh} for the impermeable beds, then, as it is known in the industry:

$$\rho_{vert} = \rho_{ss} \times \mathbf{ntg} + \rho_{sh} \times (1 - \mathbf{ntg})$$

(1)

$$1/\rho_{horiz} = (1/\rho_{ss}) \times \mathbf{ntg} + (1/\rho_{sh}) \times (1 - \mathbf{ntg})$$

(2)

Equations (1) and (2) contain three unknown averaged reservoir parameters: ρ_{ss} , ρ_{sh} , and \mathbf{ntg} . Estimates of ρ_{sh} within the reservoir interval, derived independently from the facies model or available facies data, are used next to derive and map the two remaining unknown values ρ_{ss} and \mathbf{ntg} over the spatial extent of the reservoir. Reservoir fluid type, hydrocarbon pore volume or water saturation are then derived from the mapped ρ_{ss} value within the area of the seismically defined reservoir. Statistical methods including Monte Carlo inversions may also be used for deriving hydrocarbon pore volume, net-to-gross, water saturation, and other reservoir properties from the ρ_{vert} and ρ_{horiz} inversion measurements. The derivation uses the facies model of rock properties distributions combined with Archie's Equations for the electrical resistivity of a porous rock containing fluid in the pore spaces, relative to ρ_{ss} values within the same geologic unit outside of the reservoir.

The invention described above is designed to provide an order of magnitude improvement in subsurface vertical electromagnetic resolution over current technology.

FIG. 9 is a flowchart that illustrates a preferred embodiment of the method of the invention for surface estimation of reservoir properties of a subsurface geologic formation, as just described. First, at step 900, location of the subsurface geologic formation is determined, using geological and geophysical data in the vicinity of the subsurface geologic formation. Next, at step 902, average earth resistivities above, below, and horizontally adjacent

to the subsurface geologic formation is determined, using geological and geophysical data in the vicinity of the subsurface geologic formation. Next, at step 904, dimensions for a high-current multi-mode electromagnetic source are determined to substantially maximize transmitted vertical and horizontal electric currents at the subsurface geologic formation, using the location and the average earth resistivities. Preferably, the dimensions are calculated by numerically solving the uninsulated buried low-frequency electromagnetic antenna problem, as described previously. Next, at step 906, probing frequency for a high-current multi-mode electromagnetic source is determined to substantially maximize transmitted vertical and horizontal electric currents at the subsurface geologic formation, using the location and the average earth resistivities. Again, the probing frequency preferably is calculated by numerically solving the uninsulated buried low-frequency electromagnetic antenna problem, as described previously. Alternatively, iterated 3-D modeling calculations of the subsurface geologic formation's electromagnetic response may be used to verify the dimensions and probing frequency of the high-current multi-mode electromagnetic source in steps 904 and 906. Next, at step 908, the electromagnetic source is activated at or near the surface, approximately centered above the subsurface geologic formation. Next, at step 910, a plurality of components of electromagnetic response are measured with a receiver array. Preferably, when the array of receivers 10 is positioned on land, two orthogonal horizontal electric fields, two orthogonal horizontal magnetic fields, and a vertical magnetic field are measured. Alternately, when the array of receivers 10 is positioned offshore, an additional vertical electric field is measured. Next, at step 912, geometrical and electrical parameter constraints are determined, using the geological and geophysical data. Next, at step 914, the electromagnetic response is processed using the geometrical and electrical parameter constraints to produce inverted vertical and horizontal resistivity depth images. Preferably, the components of the electromagnetic response are processed using full 3-D wave-equation methods, as described previously. 1-D inversion of the electromagnetic response is used to verify the average earth resistivities

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calculation of vertical current leakage from a continuously grounded bipole antenna of length L , using the method described above to numerically solve the uninsulated buried low-frequency electromagnetic antenna problem. This shows that most of the current leaves the grounded wire within a distance \leq

5 $L/5$ at each end of the antenna. The grounded terminating electrodes 12 each have a length of 30 meters. The grounded array and the insulated loop are not moved during the survey. Alternatively, if the number of power sources/controllers 7 is limited, or if survey logistics or terrain difficulties make simultaneous use of the eight radial grounded electrode positions impractical

10 or too costly, the eight radial partially grounded electrode positions are occupied sequentially in groups of one or more positions, in any sequential order.

A preferred procedure is to obtain substantially optimal parameter values to substantially maximize the electric field at the reservoir depth. However, as

15 an alternative procedure, a sub-optimal aspect ratio b/a could be used to reduce electrode cost, installation effort, and survey permitting. For instance, an aspect ratio $b/a = 4$ could be used. Use of this value for b/a would result in a 24.5% reduction in vertical electric field at the reservoir target, as shown in Figure 5a, and a corresponding reduction in the electromagnetic responses of

20 the reservoir to the grounded electrode excitation as measured at the surface receiver array 10.

Assume a vertically averaged resistivity of the earth of value $\rho_e = 1$ Ohm-m. Then the central operating frequency of the grounded electrode array is derived from $d/\delta = 9/4$ and $d = 2250$ meters, or $f = 0.050$ Hz. The output

25 bandwidth of the grounded electrode sources is $0.005 \leq f \leq 5.0$ Hz. Using the analysis of B. R. Spies (1989, *op. cit.*), the central operating frequency of the insulated loop source is set by $d/\delta = 1$, or $f = 0.253$ Hz. The output bandwidth of the insulated loop source is $0.025 \leq f \leq 25$ Hz.

Nine power sources/controllers 7 are placed at the surface of the earth 1.

30 Each source/controller is powered by connection to a municipal power grid, if available, or is powered by one or more generators in the field survey area.

The partially grounded electrodes 11 and the terminating electrodes 12 each consist of three uninsulated size 4/0 multi-strand copper wires. The grounded wires that comprise the grounded portion of each partially grounded electrode element 11 are buried in parallel within the top 1.0 meter of the earth's surface by means of manual digging or standard mechanical cable-laying devices. The ungrounded portions of each of the radial partially grounded electrodes 11 consist of three uninsulated size 4/0 multi-strand copper wires that are connected to the uninsulated buried electrode wires comprising the grounded portions. The ungrounded portions of each radial electrode are laid on the surface of the earth. Electrical contact of the grounded radial electrodes and the terminating electrodes is maintained with the earth by periodically wetting the buried electrode areas with water, as needed according to local ground moisture conditions. The loop source 6 consists of one single-conductor multi-strand insulated size 4/0 copper wire. Power connection cables 8 and 9 are electrically rated according to U.S. NEMA (National Electrical Manufacturing Association) codes and standards to

carry the current delivered to the grounded electrodes 11,12 and to the insulated loop 6, respectively.

Electromagnetic receivers 10, such as Electromagnetic Instruments, Inc. (EMI) type MT-24/NS™ or equivalent, are positioned over the surface of the earth 1 within a radial distance $r = (x^2 + y^2)^{1/2} = 5000$ meters from the center of the array, but not within 25 meters of any grounded electrode 11, 12 or the insulated loop 6, to minimize source-generated noise and saturation of the receiver signals. The receivers are positioned on a uniform grid as shown in Figure 6, with a lateral spacing of $x = y = 100$ meters, within a radius of 2000 meters from the center of the array, and on a uniform grid with a lateral spacing of $x = y = 300$ meters from a radius of 2500 meters to a radius of 5000 meters from the center of the array. Each five-channel receiver measures two components (x and y directions) of the horizontal electric field, two components (x and y directions) of the horizontal magnetic field, and one component (z direction) of the vertical magnetic field. The receivers are modified by standard industry methods including feedback stabilization so that the phase accuracy of the magnetic field induction sensors (EMI type BF-4™ or equivalent) is greater than or equal to 0.10 degrees in the full frequency range of the survey ($0.005 \leq f \leq 25$ Hz).

The five-component receivers are deployed simultaneously in large groups (16 or more) within the survey area, with as many receiver groups deployed as possible and practical for the local conditions of the survey (e.g. terrain difficulties, logistical support). Data are gathered for each receiver group by a central processing unit (EMI type FAM/CSU™ or equivalent). Differential GPS geodetic methods are used to measure the positions (x , y , z) of all receivers to within 0.1 meters accuracy. The GPS signal is also used for phase synchronization (timing) of all receiver data.

The receiver data are collected in three ways. First, the receiver data are collected as time records with all sources 7 turned off, to record zero excitation currents. These data are collected over a length of time that is sufficient to record raw stacked magnetotelluric data having three-sigma errors less than or equal to 5% over the frequency range $0.0025 \leq f \leq 25$ Hz.

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Typically, collection of this data will take 1-10 days, depending upon local conditions and the logistics of receiver deployment. This first set of receiver data is magnetotelluric data. Second, the insulated loop source is energized using a standard electromagnetic industry bipolar square wave current from its attached power source/controller 7, as shown in FIG. 7. In this preferred embodiment of the method of the present invention, current pulse on-time, T_1 equals current waveform off-time, T_2 , that is, $T_1 = T_2$, but this is not a limitation of the method. Other source current waveforms may also be used for the insulated loop source current, including sinusoidal waveform combinations and pseudo-random sequences as well known to one skilled in the art, provided the insulated loop source frequency range is as stated. The receiver responses are collected using time-domain measurements acquired during the current waveform off-time, T_2 in FIG. 7. The duration of the current pulse on-time, T_1 in FIG. 7 (and hence also the off-time T_2), is set at three values, 0.01, 1.0, and 10.0 seconds. Sufficient repetitions (typically 50 to 1000) of the loop source current are made at each on-time value so that the raw stacked data time series data have three-sigma errors less than or equal to 1% over the frequency range $0.025 \leq f \leq 25$ Hz. This second set of receiver data is vertical magnetic dipole data. Third, the insulated loop source is turned off (zero current) and the eight partially grounded electrodes 11, 12 are simultaneously energized in phase. Alternatively, if the number of power sources/controllers is limited, the partially grounded electrodes are energized separately in groups of one or more, in any sequential order. Each of the eight power sources/controllers 7 produces a standard electromagnetic industry bipolar square wave current pulse, as shown in FIG. 7, with the duration of the current pulse on-time, T_1 in FIG. 7, (and hence T_2) set at three values, 0.05, 5.0, and 50.0 seconds. Other source current waveforms may also be used for the grounded source current, including sinusoidal waveform combinations and pseudo-random sequences as well known to one skilled in the art, provided the grounded electrode source frequency range is as stated. Sufficient repetitions (typically 50 to 1000) of the grounded electrodes' source currents are made at each on-time value so that the raw stacked data time

series data have three-sigma errors less than or equal to 1% over the frequency range $0.005 \leq f \leq 5$ Hz. This third set of receiver data is grounded radial electrode data.

The three sets of receiver data are processed in the following way. After noise suppression using standard industry methods as described above, the second set of vertical magnetic dipole data and the third set of grounded radial electrode measurements are converted to the complex frequency-wavenumber domain using standard industry 2-D Fourier and Radon transform techniques. The first set of magnetotelluric data and the second set of vertical magnetic dipole data are merged together in the frequency-wavenumber domain, for each electromagnetic tensor component of the data. The merged magnetotelluric and vertical magnetic dipole data sets are inverted, and the grounded radial electrode data set is inverted separately. Then the merged magnetotelluric and vertical magnetic dipole data and the grounded radial electrode data are inverted jointly, as discussed in D. Jupp and K. Vozoff, *Geophys. Prospecting*, v. 25, 460-470, 1977. The magnetotelluric data, the vertical magnetic dipole data, and the grounded radial electrode data are also inverted separately. All data inversions use the 3-D frequency-domain finite-difference fully nonlinear methods of G. A. Newman and D. L. Alumbaugh (1996, 1997, *op. cit.*), modified to allow for the geometries of the grounded radial electrode and the insulated loop source current arrays. Depth and parameter value constraints are enforced during the inversion, using sharp-boundary methods (G. Hoversten et al, 1998, *op. cit.*) and integral resistance and conductance bounds within the update region of the nonlinear inversion 3-D mesh that contains the reservoir target, combined with minimum-gradient support techniques (O. Portniaguine and M. Zhdanov, 1998, *op. cit.*). The nonlinear inversion update region is centered on the target reservoir, and extends 100 meters above and below the reservoir and 200 meters laterally from each reservoir edge.

30 The starting model for both the merged magnetotelluric and vertical magnetic dipole data inversion and the grounded radial electrode data inversion is an interpreted seismic depth model in which the mechanical

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FIG. 8 shows the complex magnitude of the calculated radial component $\mathbf{E}_r = (\mathbf{E}_x^2 + \mathbf{E}_y^2)^{1/2}$ of the surface electric field response from the example target reservoir described above, due to excitation by the grounded electrode array. The example reservoir is assumed to have a vertical thickness of 20 meters and a vertically averaged resistivity of 100 Ohm-m. The electromagnetic response was calculated using the SYSEM 3-D integral equation computer code developed at the University of Utah's Consortium for Electromagnetic Modeling and Inversion. This electric field component response is normalized to the uniform earth (halfspace) response, and is shown on FIG. 8 as a function of radial distance from the center of the array and of the source frequency, along the $\mathbf{x} = 0$ (or $\mathbf{y} = 0$) axis. Most of the normalized \mathbf{E}_r response is contained within $\mathbf{r} \leq 1300$ meters, and has a maximum value of approximately 33% at $\mathbf{r} = 0$ at the lowest survey frequency

($f = 0.005$ Hz). The large normalized E_r value at $r = 1500$ meters is a local effect of the inner radial electrode.

The benefits provided by this invention include at least the following two. The first benefit is cost and cycle-time reduction in hydrocarbon exploration, development, and production activities, including reducing exploration drill-
5 well risk, improving discovered-undeveloped reservoir delineation and assessment, and improving reservoir monitoring and depletion. The second benefit is improved business capture of new exploration ventures and field commercializations by offering unique, proprietary reservoir properties
10 estimation technology.

It should be understood that the invention is not to be unduly limited to the foregoing which has been set forth for illustrative purposes. Various modifications and alternatives will be apparent to those skilled in the art without departing from the true scope of the invention, as defined in the
15 following claims.

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I claim:

1. A method for surface estimation of reservoir properties of a subsurface geologic formation, comprising the steps of:

5 determining location of and average earth resistivity above, below, and horizontally adjacent to the subsurface geologic formation using geological and geophysical data in the vicinity of the subsurface geologic formation;

determining dimensions and probing frequency for an electromagnetic source to substantially maximize transmitted vertical and horizontal electric
10 currents at the subsurface geologic formation using the location and the average earth resistivity;

activating the electromagnetic source at or near surface, approximately centered above the subsurface geologic formation;

measuring a plurality of components of electromagnetic response with a
15 receiver array;

determining geometrical and electrical parameter constraints, using the geological and geophysical data; and

processing the electromagnetic response using the geometrical and electrical parameter constraints to produce inverted vertical and horizontal
20 resistivity depth images.

2. The method of claim 1, further comprising the step of:

combining the inverted resistivity depth images with the geological and geophysical data to estimate the reservoir properties.

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3. The method of claim 2, wherein the step of determining dimensions and probing frequency is accomplished by numerically solving the uninsulated buried low-frequency electromagnetic antenna problem for the vertical electrical current at the subsurface geologic formation.

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4. The method of claim 2, wherein the electromagnetic source comprises:

5. The method of claim 4, wherein each circular electrode comprises one
5 or more electrically uninsulated conductors.

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11. The method of claim 8, wherein the radial electrodes are continuously grounded only within a distance less than one half of the length of the radial electrode, from each end.

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two orthogonal horizontal magnetic fields; and
a vertical magnetic field.

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two orthogonal horizontal magnetic fields;

a vertical electric field.

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verifying the average earth resistivities above, below, and horizontally adjacent to the subsurface geologic formation, using the plurality of components of electromagnetic response measured with the receiver array.

30

applying 3-D wave-equation data processing to the electromagnetic response.

19. The method of claim 2, wherein the data processing includes data
5 noise suppression, source deconvolution, and model-guided inversion.

20. The method of claim 7, wherein the steps of activating the electromagnetic source and measuring the electromagnetic response further comprises the steps of:

10 measuring a first electromagnetic response without activating the
electromagnetic source;

measuring a second electromagnetic response while activating only the third circular insulated electrode; and

measuring a third electromagnetic response while activating only the
15 grounded uninsulated electrodes.

21. The method of claim 20, wherein the step of applying data processing further comprises the steps of:

merging the first and second electromagnetic responses to produce a
20 fourth electromagnetic response;

inverting the first electromagnetic response;

inverting the second electromagnetic response;

inverting the third electromagnetic response;

inverting the fourth electromagnetic response; and

25 inverting jointly the third and fourth electromagnetic responses.

A method for surface estimation of reservoir properties, wherein location of and average earth resistivities above, below, and horizontally adjacent to the subsurface geologic formation are first determined using geological and geophysical data in the vicinity of the subsurface geologic formation. Then dimensions and probing frequency for an electromagnetic source are determined to substantially maximize transmitted vertical and horizontal electric currents at the subsurface geologic formation, using the location and the average earth resistivities. Next, the electromagnetic source is activated at or near surface, approximately centered above the subsurface geologic formation and a plurality of components of electromagnetic response is measured with a receiver array. Geometrical and electrical parameter constraints are determined, using the geological and geophysical data. Finally, the electromagnetic response is processed using the geometrical and electrical parameter constraints to produce inverted vertical and horizontal resistivity depth images. Optionally, the inverted resistivity depth images may be combined with the geological and geophysical data to estimate the reservoir fluid and shaliness properties.

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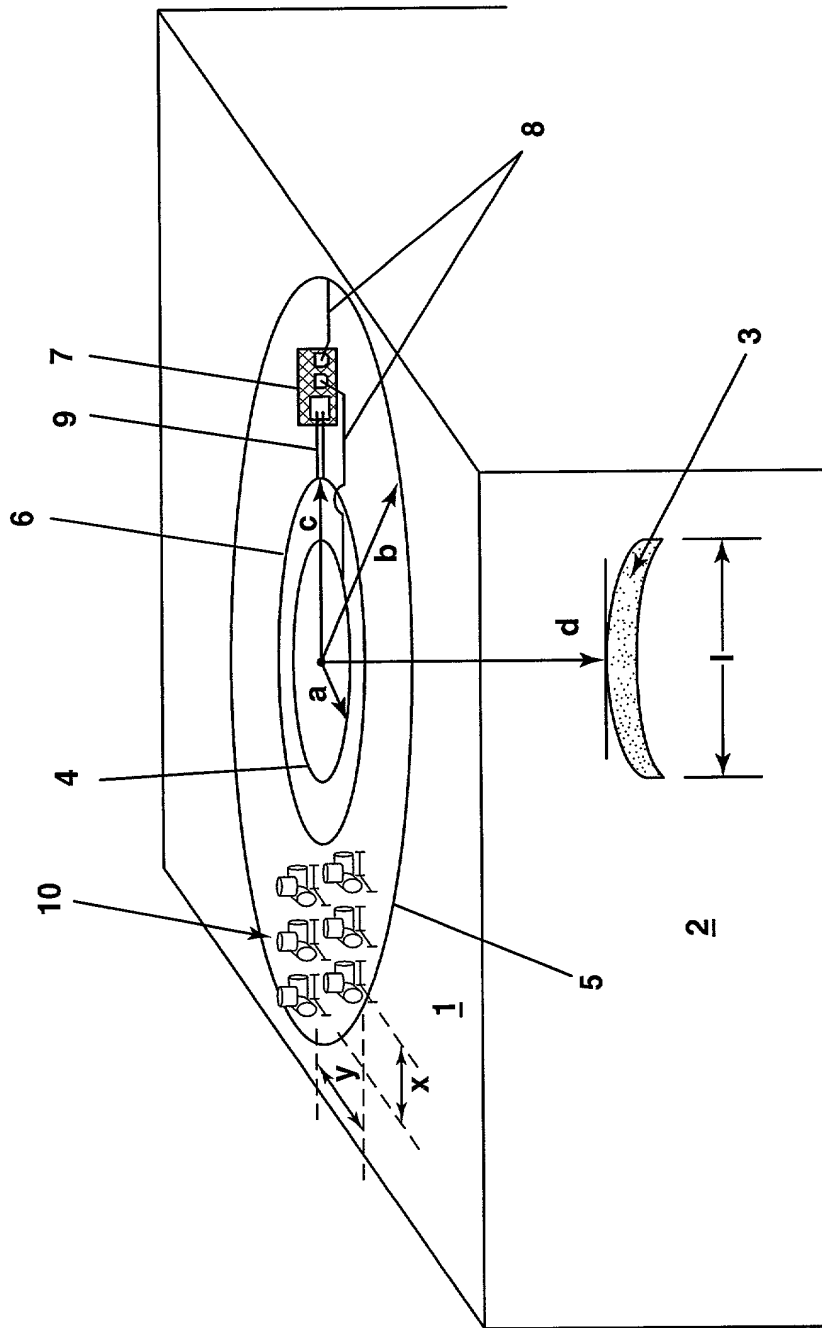


FIG. 1

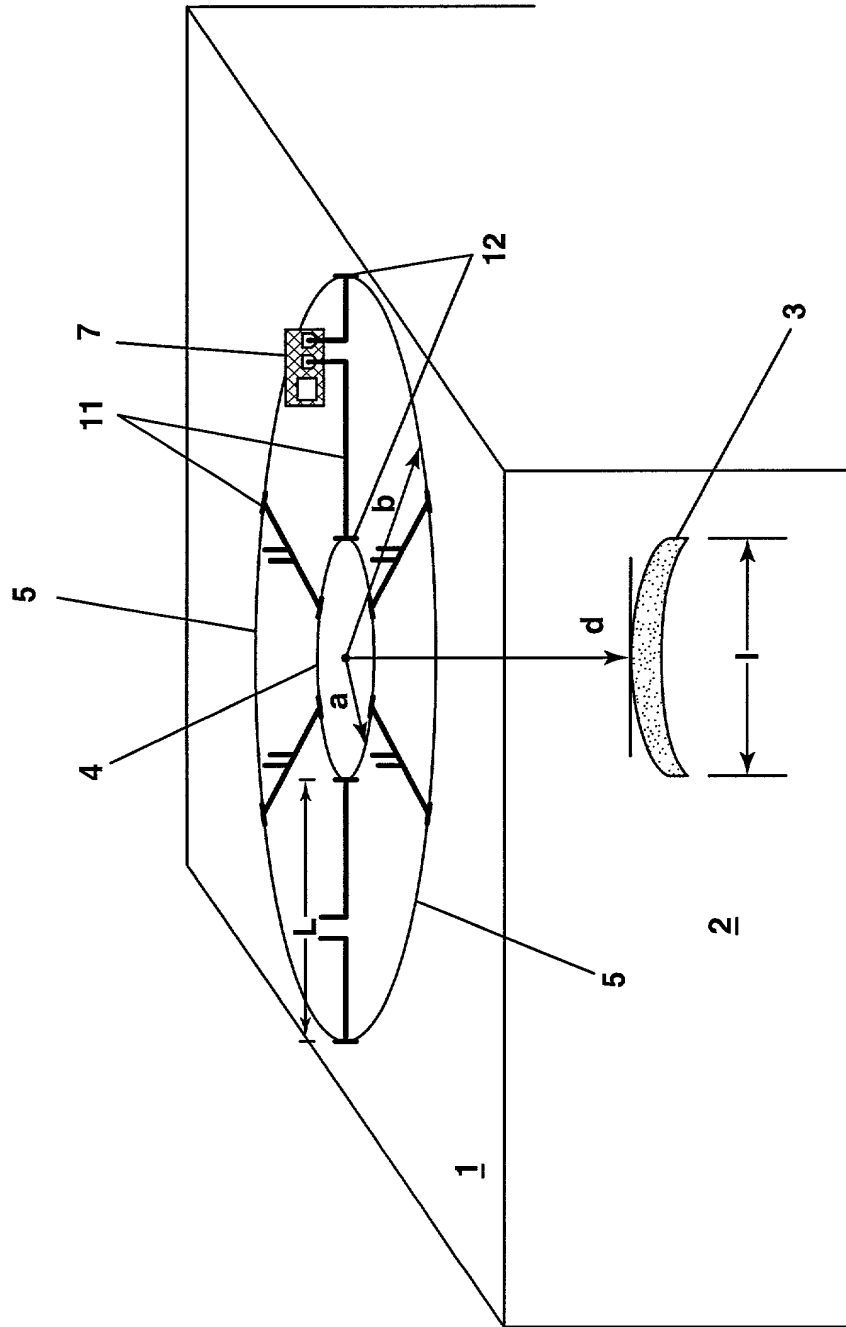


FIG. 2

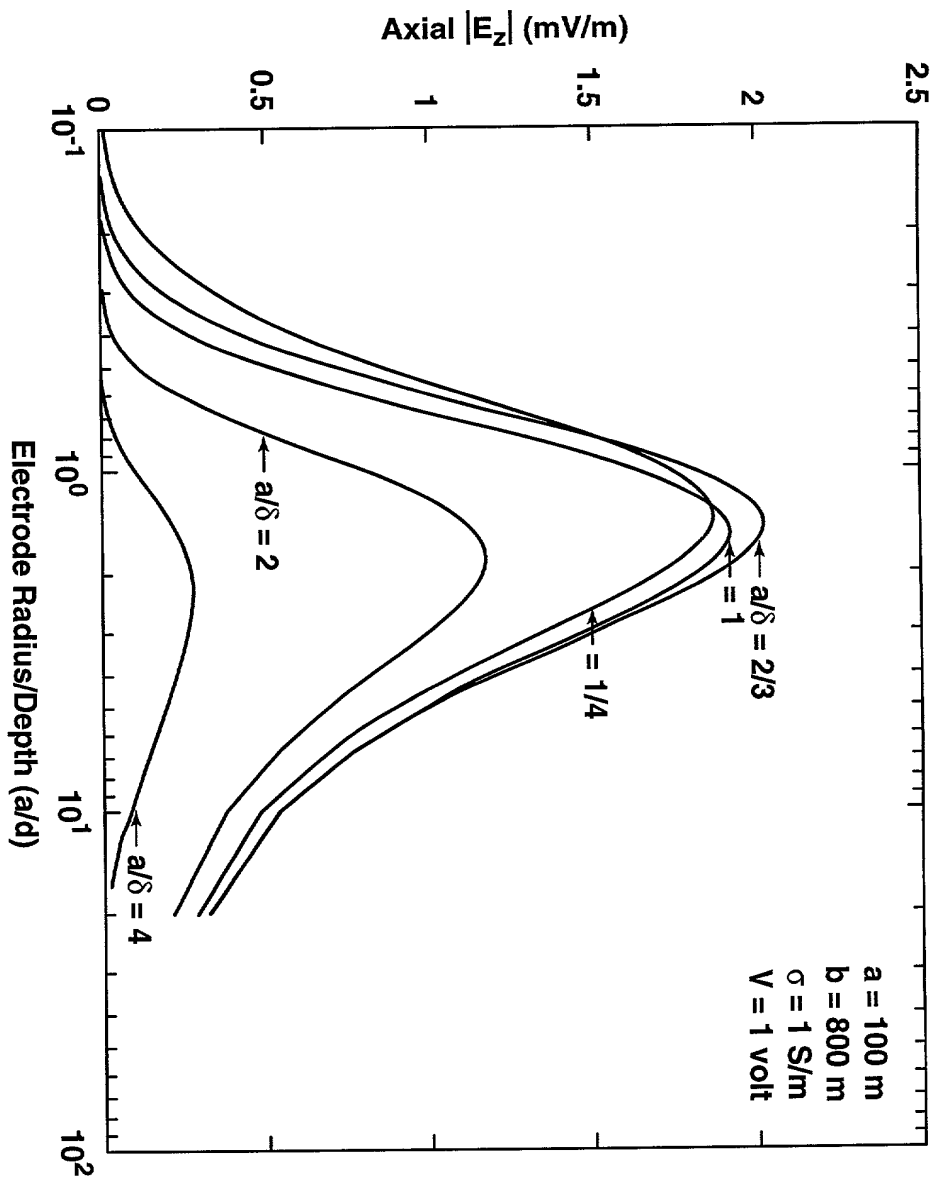


FIG. 3

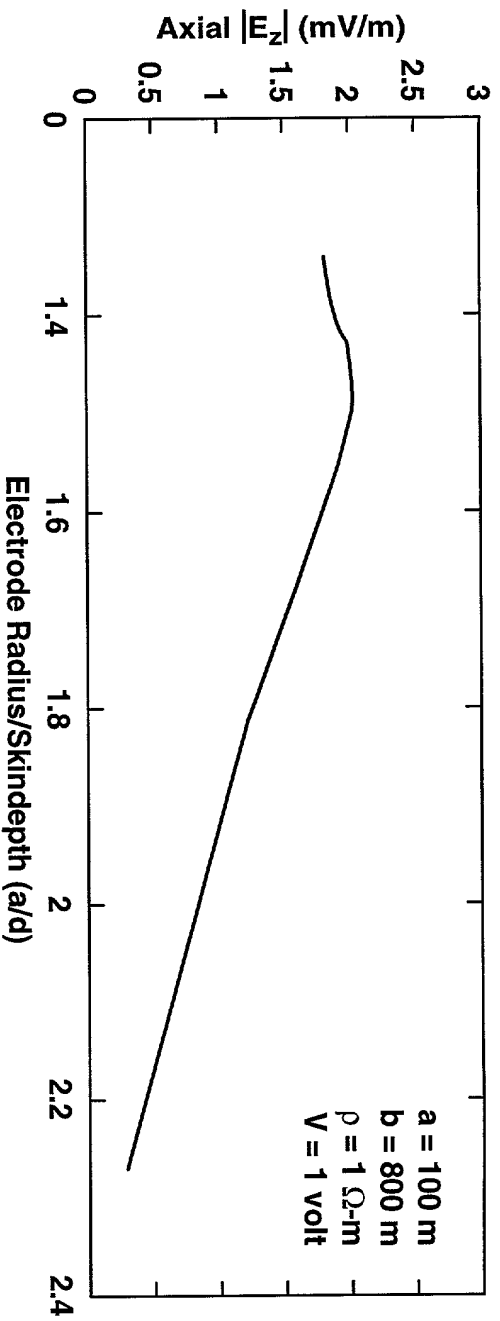


FIG. 4a

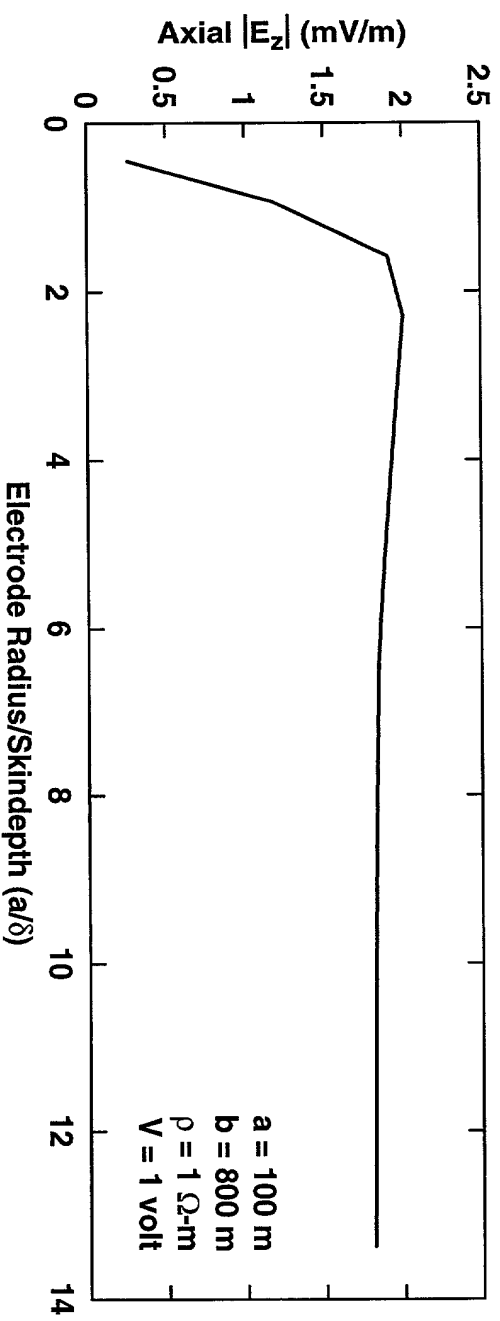


FIG. 4b

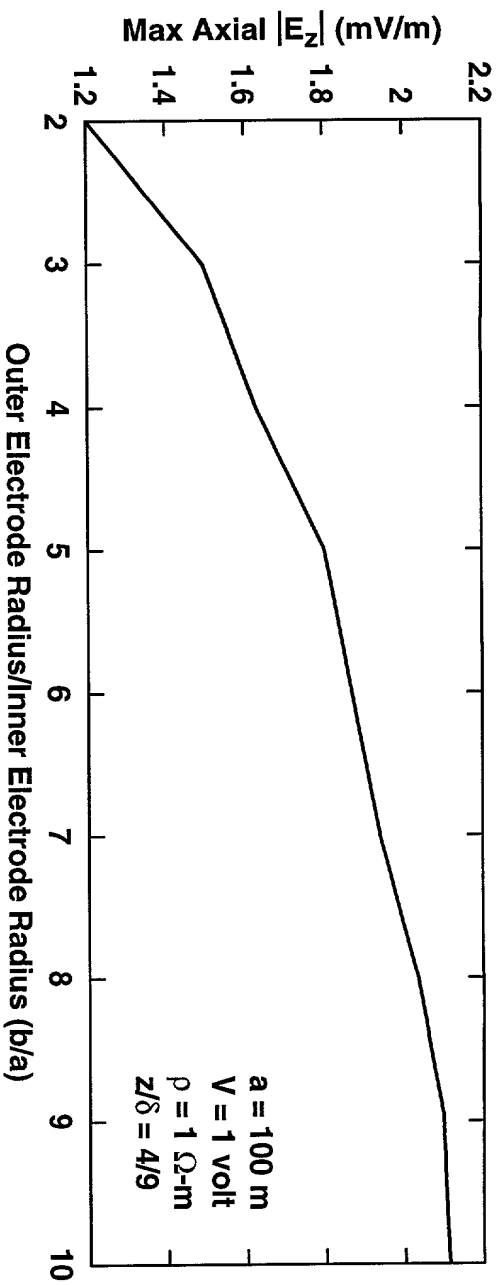


FIG. 5a

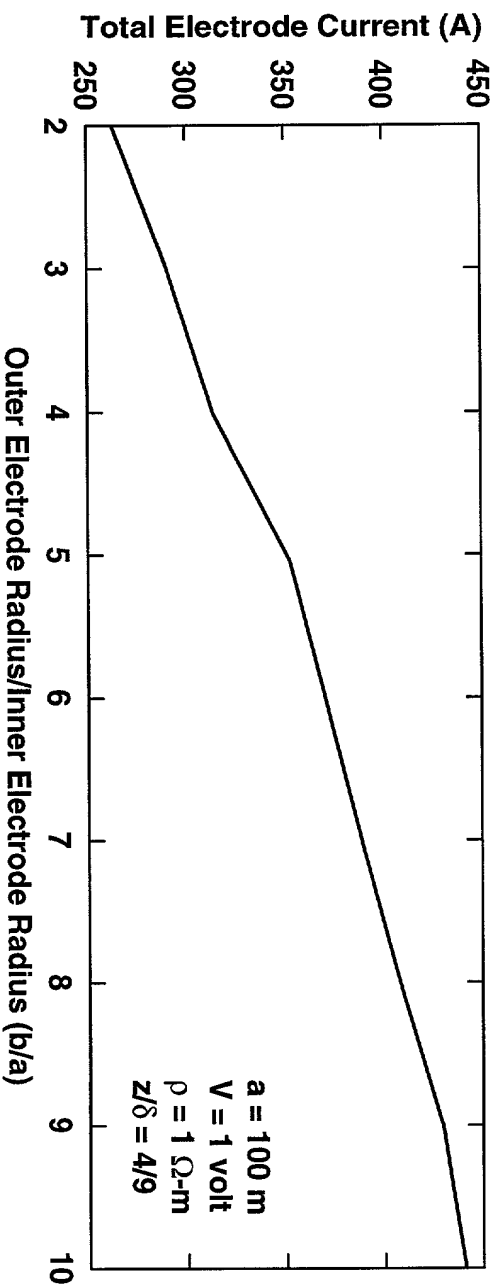


FIG. 5b

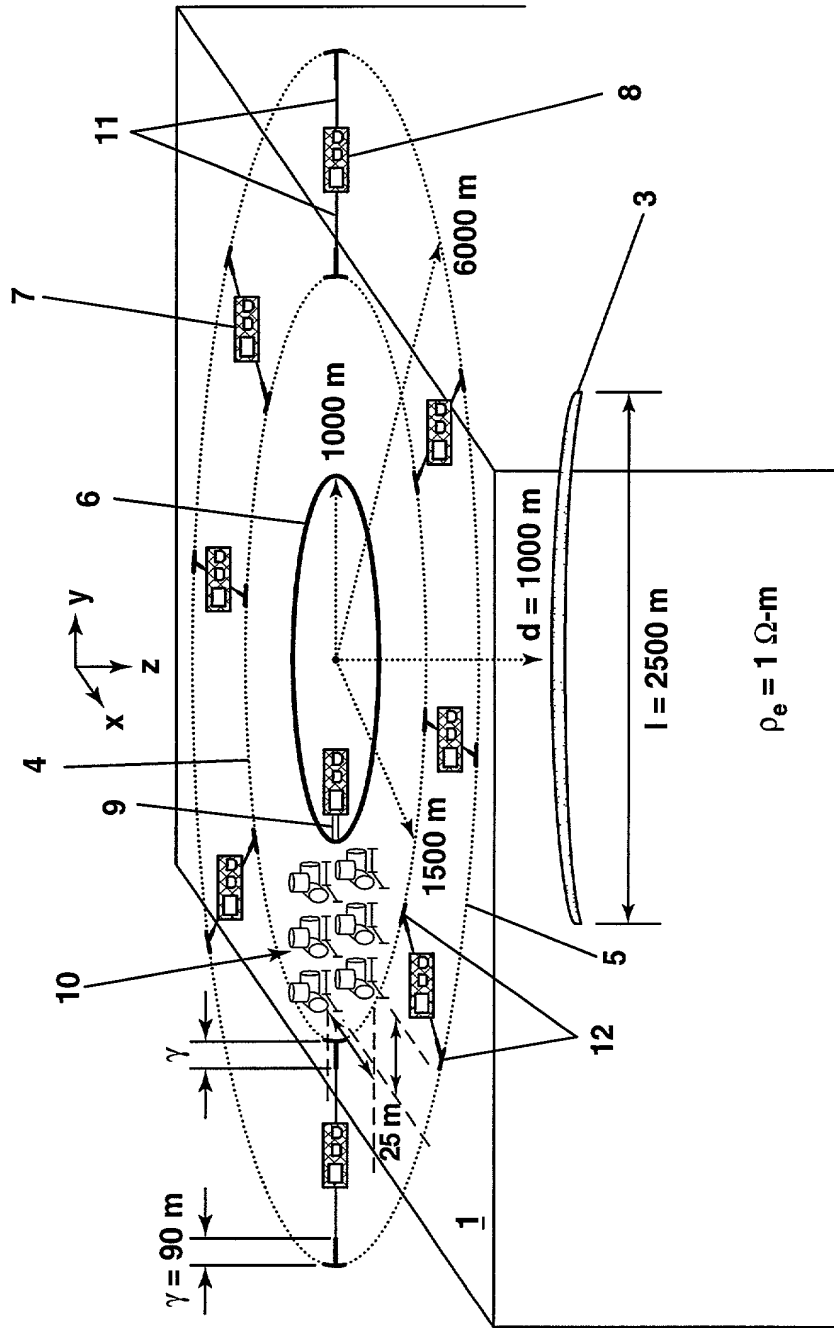


FIG. 6

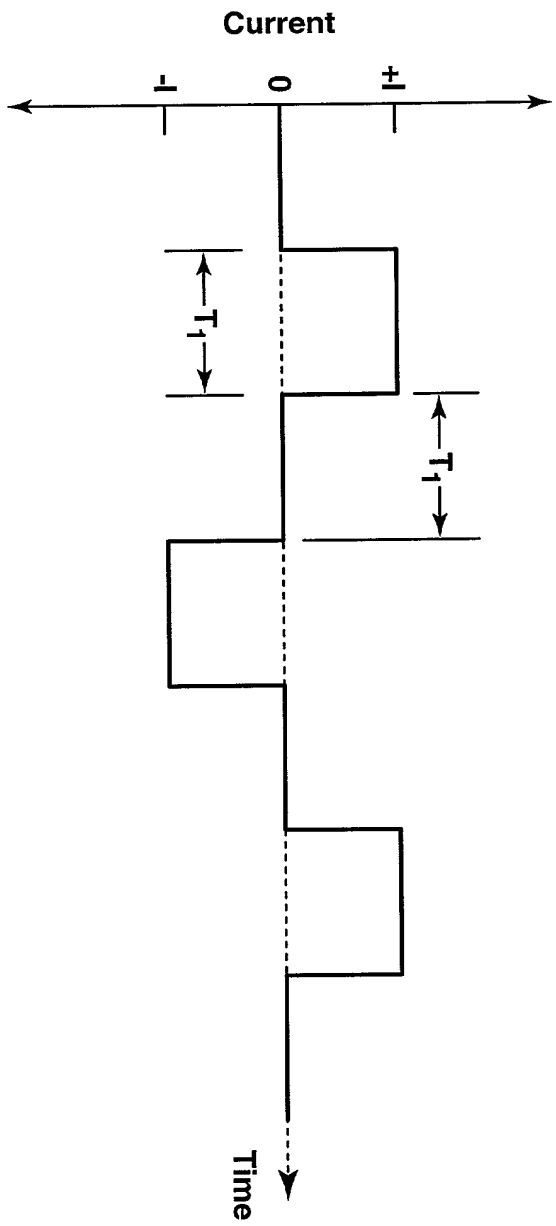


FIG. 7

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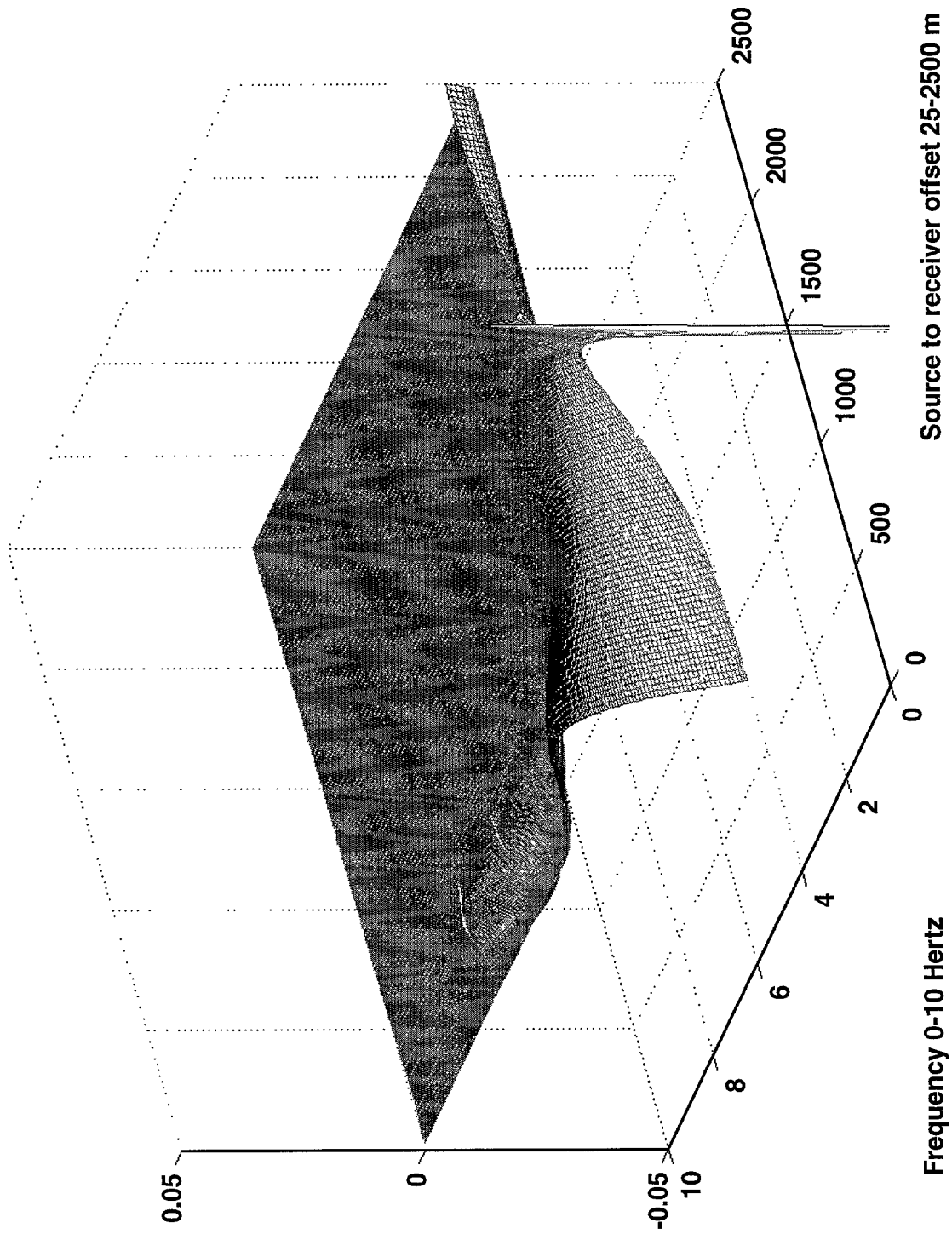


FIG. 8

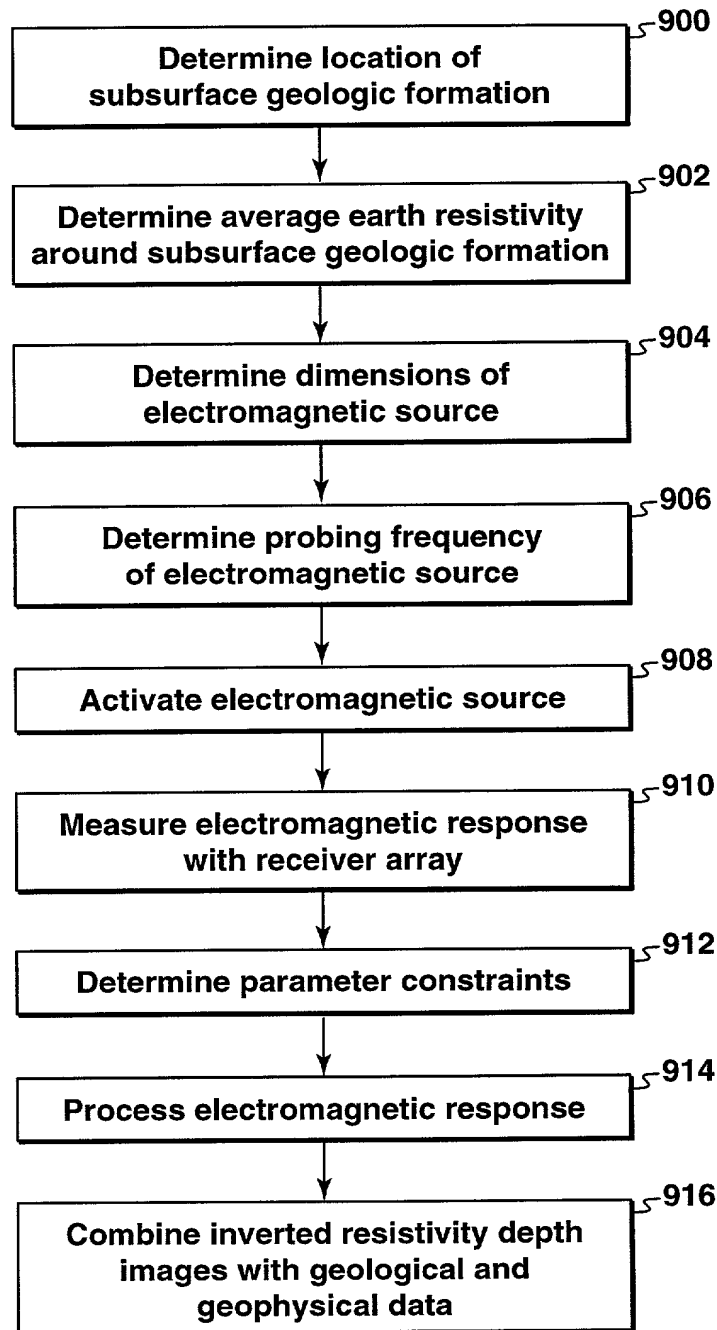


FIG. 9

Docket No.
PM 98.076

Declaration and Power of Attorney For Patent Application

English Language Declaration

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name,

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

REMOTE RESERVOIR RESISTIVITY MAPPING

the specification of which

(check one)

☒ is attached hereto.

☐ was filed on _____ as United States Application No. or PCT International Application Number _____ and was amended on _____ (if applicable)

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose to the United States Patent and Trademark Office all information known to me to be material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, Section 119(a)-(d) or Section 365(b) of any foreign application(s) for patent or inventor's certificate, or Section 365(a) of any PCT International application which designated at least one country other than the United States, listed below and have also identified below, by checking the box, any foreign application for patent or inventor's certificate or PCT International application having a filing date before that of the application on which priority is claimed.

Prior Foreign Application(s)			Priority Not Claimed
_____ (Number)	_____ (Country)	_____ (Day/Month/Year Filed)	<input type="checkbox"/>
_____ (Number)	_____ (Country)	_____ (Day/Month/Year Filed)	<input type="checkbox"/>
_____ (Number)	_____ (Country)	_____ (Day/Month/Year Filed)	<input type="checkbox"/>

I hereby claim the benefit under 35 U.S.C. Section 119(e) of any United States provisional

60/154,114

09/15/99

(Application Serial No.)

(Filing Date)

(Application Serial No.)

(Filing Date)

(Application Serial No.)

(Filing Date)

I hereby claim the benefit under 35 U. S. C. Section 120 of any United States application(s), or Section 365(c) of any PCT International application designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of 35 U.S.C. Section 112, I acknowledge the duty to disclose to the United States Patent and Trademark Office all information known to me to be material to patentability as defined in Title 37, C. F. R., Section 1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application:

(Application Serial No.)

(Filing Date)

(Status)
(patented, pending, abandoned)

(Application Serial No.)

(Filing Date)

(Status)
(patented, pending, abandoned)

(Application Serial No.)

(Filing Date)

(Status)
(patented, pending, abandoned)


I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

POWER OF ATTORNEY: As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith. *(list name and registration number)*

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Second inventor's signature	Date
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